A study to improve the measurement accuracy of stress intensity factor by the infrared method

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Abstract

Stress intensity factors evaluated by an infrared stress analysis method have usually been lower than analytical values. In order to reveal the source of the error, an unsteady heat conduction analysis under cyclic loading was carried out and the results were compared with the measurement values. As a result, it was clear that the errors of stress intensity factor between evaluated values and analytical values were caused not by heat conduction but by the plastic zone size of a crack tip. Then, the hybrid method adopting a numerical analysis was developed in order to improve the measurement accuracy of stress intensity factor by the infrared method. The stress intensity factors revalued by this hybrid method were almost somewhat higher than analytical values.

1 Introduction

The local stresses and strains near notches or cracks are very important for fracture analyses of cyclically loaded structure components. Thus, a number of experimental methods such as a photoelasticity method and numerical methods such as a finite element analysis have been developed to evaluate stresses and strains near notches or cracks. Among those methods, an infrared stress measurement method, which is based on the measurement of infrared radiation emitted from the surface of a body, can measure a two-dimensional stress distribution of real structure components without preparing special models like a photoelasticity method.

When this technique was used to evaluate the stress intensity factors for CT and CCT specimens, the determined values tended to be somewhat lower than numerical results, and the error increased in proportion to those values not to concern with the stress ratio[1]. Thus, in this study, the effect of heat conduction
in a body of sheet specimens under cyclic loading was investigated by a finite
differential analysis to examine the source of the error, and the results were
compared with experimental results. Also, the hybrid method adopting a
numerical analysis was developed in order to improve the measurement accuracy
of stress intensity factor by infrared method.

2 Theory of the thermoelastic stress analysis

Based on a theoretical treatment of the thermoelastic effect by Lord Kelvin [2],
the temperature change associated with adiabatic elastic deformation in a body
can be expressed in the form:

\[ \Delta T = -\frac{E\alpha T}{\rho C_v(1-2\nu)} \sum_{i=1,2,3} \Delta \varepsilon_{ii} = -K_n T \sum_{i=1,2,3} \Delta \sigma_{ii} \]  

(1)

where \( \Delta T \) is change in temperature, \( E \) is the Young’s modulus, \( \alpha \) is the
coefficient of linear thermal expansion, \( T \) is absolute temperature, \( \rho \) is the mass
density, \( C_v \) is the specific heat at constant strain, \( \nu \) is the Poisson’s ratio, \( \Delta \varepsilon_{ii} \) is
the normal strain change, \( K_n \) is the thermoelastic constant, \( \Delta \sigma_{ii} \) is the sum of
normal stress changes. Therefore, only the principal stress sum can be measured
by an infrared stress analysis method.

3 Infrared stress analysis method

Figure 1 shows the schematic of the infrared stress analysis system using in this
study. Cyclic load is applied to the specimen. An infrared camera, of which
sensitivity is 0.001 K corresponded to 1 MPa in steel, generates a signal in phase
with the load signal in response to the infrared emission from the surface of a
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specimen. Since the temperature changes due to thermoelastic effect are very small, the generated signals are averaged in the measurement time in order to improve the S/N ratio. The image of change in temperature $\Delta T$ is obtained by subtracting the temperature image in minimum load $T_{\text{min}}$ from the one in maximum load $T_{\text{max}}$.

4 Test procedures

Two types of specimen were prepared in this study, one was CT specimen made of JIS SM490A steel, and the other was CCT specimen made of JIS S45C steel. The mechanical properties of the materials used are given in Table 1. The configurations of two type specimens are shown in Figure 2.

Table 1: Mechanical properties of the materials used.

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield stress (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM490A</td>
<td>402</td>
<td>520</td>
<td>27</td>
</tr>
<tr>
<td>S45C</td>
<td>450</td>
<td>550</td>
<td>30</td>
</tr>
</tbody>
</table>

The pre-cracking CT specimens were cyclically loaded at frequency of 5Hz using a servo-hydraulic fatigue machine of 196 kN capacity. The stress waveform was sinusoidal and the stress ratio was 0.1. While CCT specimens were loaded at different levels of frequency of 1, 5, 10 and 15 Hz in order to investigate the effect of heat conduction in the body. Prior to the stress measurement, all specimens were cleaned with acetone and then coated with matt black spray paint to maximize their emissivity. The stress measurement by thermoelastic technique was carried out using an infrared stress analysis system developed by JEOL. The typical example of stress contour around a crack tip is

Figure 2: The configurations of CT and CCT specimen.
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shown in Fig. 3.

4 Effect of heat conduction

4.1 Unsteady heat conduction analysis

The unsteady heat conduction analysis under cyclic loading was carried out by finite differential method (FDM) in order to investigate the effect of the heat conduction in a specimen on measured value. Prior to the unsteady heat conduction analysis, the stresses of CCT specimens were analyzed by the finite element method (FEM) under the plane stress condition using a two-dimensional mesh. Considering the symmetrical configuration, one fourth of the CCT specimen was analyzed. The temperature range of each node was obtained by substituting the values of normal stresses analyzed by the finite element method into the eqn (1) and it was found that the temperature waveform was sinusoidal.

4.2 Experimental and analytical results

Figure 3: Typical example of stress contour around a crack tip.

\[ \Delta K = 18.5 \text{ MPa m}^{1/2} \]

Figure 4: The distribution of the principal stress sum in the ligament analyzed by FDM.

Figure 5: The distribution of the principal stress sum in the ligament measured.

Figure 6: Effect of loading frequency on \( \Delta K \).
Figure 4 shows the distribution of the principal stress sum along the ligament of CCT specimen analyzed by FDM. Also, the measurement results are shown in Figure 5. As can be seen those figures, it is clear that the stress distributions were affected by heat conduction in the specimen. Then stress intensity factor ranges $\Delta K$ were calculated by the extrapolation method often used in the photoelasticity and compared with experimental results. Figure 6 shows the relationship between $\Delta K$ and the loading frequency. However, each value of $\Delta K$ was hardly affected by the loading frequency and practically constant. The cause is that the stresses of crack vicinity, which affect the accuracy of $\Delta K$, can not be measured accurately by an infrared technique due to plastic deformation around the crack tip.

5 Hybrid method

The stress intensity factor range evaluated by the extrapolation method underestimated compared with the actual value since the stresses near crack tip can not be measured accurately due to plastic deformation around the crack tip. Accordingly, a technique aided by the finite element method for estimating the stresses near the crack tip from the measured values in parts where there were no effects of plastic deformation was devised.

5.1 Principle of the hybrid method

In a infrared stress measurement technique, only the stress invariant of the first order $J_1$ can be measured and resolution of stress components was thought to be impossible. Then, the methods to overcome the disadvantage of this technique have been developed [3][4]. In the same way, it is possible to evaluate the stress intensity factor range using the stress values of the part which are not affected by the plastic deformation near crack tip.

Figure 7: Schematic of the hybrid method adopting numerical analyses.
As shown in Figure 7, the region surrounded in the boundary $\Gamma$, which is the part of specimen, is considered. The stress values surrounded in this boundary are known from the infrared measurement results but the load boundary conditions along $\Gamma$ are unknown. When a unit force in the nominal and then tangential direction is applied to a point $j (j = 1$ to $N)$ along the boundary $\Gamma$, the stress at a point $i (i = 1$ to $M)$ in the region occurring by this unit force should be $\sigma_y^*$. Assuming that the force actually acting on the point $j$ is $P_j$, stress $\sigma_y$ in the point $i$ is shown as follows according to the superposition principle:

![Figure 8: Simulation model. Dimensions are in mm.](image1)

![Figure 9: The stress image measured by infrared method used for the determination of the boundary conditions.](image2)

![Figure 10: Distribution of stresses along the ligament analyzed by hybrid method.](image3)
\begin{equation}
\sigma_{ij} = \sum_{j=1}^{N} \sigma_{ij} * P_j \quad i = 1 \sim M, \ j = 1 \sim N. \tag{2}
\end{equation}

In order to determine the optimum values of \( P_j \), the least square method is applied to \( S \):

\begin{equation}
S = \sum_{i=1}^{M} \left( \sigma_{ij} - \sum_{j=1}^{N} \sigma_{ij} * P_j \right)^2 \quad i = 1 \sim M, \ j = 1 \sim N. \tag{3}
\end{equation}

The optimum values of \( P_j \) must satisfy the following equation:

\[ \frac{\partial S}{\partial P_j} = 0. \tag{4} \]

Resolving a set of \( N \) linear simultaneous equation, \( P_j \) is determined. Accordingly, the stresses near crack tip are calculated by FEM under the determined boundary conditions.

### 5.2 Results of evaluation

The finite element mesh used in this method, which is shown in Figure 8, consisted of 702 4-node isoparametric elements. FE analyses were carried out under the plane stress condition. The Young’s modulus \( E \) was 206GPa and the Poisson’s ratio was 0.3. Figure 9 shows an example of the stress image of CT specimen used for this method, and the stress values surrounded with the dotted line are used to determine the boundary conditions \( P_j \). Figure 10 shows the stress distribution along the ligament estimated by the hybrid method at \( \Delta K = 11.1 \text{MPa} \text{m}^{1/2} \). The stress values estimated by this method were agreed well with the

![Figure 11](image)

Figure 11: Comparison between the values of the hybrid method and analytical values.
referred values. It was also tended to be similar at the other values of $\Delta K$. Then, the stress intensity factor ranges were evaluated using the stress values analyzed by this method. Figure 11 shows comparison of $\Delta K$ between the values derived from the hybrid method and analytical values. The results of the extrapolation method are also shown in this figure. As can be seen in this figure, it was found that $\Delta K$ obtained by the hybrid method tended to be larger than the values of the extrapolation method though they were scattered around the analytical values.

6 Conclusions

In this paper, in order to improve the measurement accuracy of stress intensity factors by the infrared stress analysis method, the cause of the error between measurement results and analytical values was clarified by means of unsteady heat conduction analysis. Then, the hybrid method to overcome the disadvantage that the stresses near crack tip can not be measured by the infrared method is developed. The obtained results are summarized as follows:

(1) The errors of stress intensity factor between estimated values and analytical results were caused not by heat conduction but by the plastic deformation around crack tips.
(2) The stresses calculated by the hybrid method were agreed well with the measurement values.
(3) Stress intensity factor ranges evaluated by the hybrid method were often larger than the values obtained by the extrapolation method.

References


